THE WORK OF A MODERN OBSERVATORY.[1]

BY GEORGE ELLERY HALE.

We have been fortunate enuf to live in a golden age of science, an age rich in discoveries of instruments, methods and ideas readily applicable in the domain of astronomy. Each one of us, from the amateur, whose chief equipment may consist of an unquenchable thirst for knowledge, to the endowed investigator, lacking in no material means, may profit by the extraordinary advances of recent years. Half a century ago the equatorial telescope and meridian circle, with clock and micrometer, were the sole instruments of the observatory. They were used mainly to measure the positions and motions of the heavenly bodies, and altho the foundations of astrophysics had been laid long before, the means available for the erection of its superstructure were few and insignificant when compared with those we now enjoy.

The two chief factors in the new advance appeared, curiously enuf, within the same decade. The sensitive plate, first employed by DAGUERRE in 1839, was utilized at the Harvard Observatory for stellar photography in 1857 and applied to the registration of the solar image at Kew in the following year. The spectroscope, chief instrument of the student of inorganic evolution, first proved its worth almost simultaneously with the publication of the *Origin of Species* in 1859, when KIRCHHOFF and BUNSEN determined by its aid the chemical composition of the Sun. BOND's experiments in stellar photography at Harvard had been made with the wet collodion plate, but in 1876 HUGGINS first applied dry plates to the photography of stellar spectra. To-day comparatively few astronomical observations are made visually. The spectroscope, once a minor accessory of the telescope, is now more properly regarded in some classes of work as the primary instrument, with the telescope as its indispensable auxiliary. Originally a simple laboratory appliance, suited only for qualitative purposes, it has

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developed into a measuring instrument of extraordinary flexibility and power, yielding results which surpass in precision the most refined measurements of visual astronomy.

Supplementing and in some cases superseding the spectroscope, there have arisen the interferometer in its various forms, the MICHELSON echelon and the LUMMER-GEHRCKE parallel plate, each applicable with advantage to certain kinds of light analysis. Instruments of surprising sensitiveness, including the thermopile, the bolometer, the radiometer, the radiomicrometer, and the selenium and photo-electric cell, have brought to knowledge radiations far beyond the range of the eye or the photographic plate, and disclosed stellar variations in brightness too minute for former devices to reveal. At the same time telescopes have increased greatly in aperture and in optical and mechanical perfection, while new photometers, clocks and other auxiliaries of various kinds have led to more refined astronomical measurements, which have reached their highest precision thru the improvement of the photographic method. For the study of astronomical photographs, a large class of special machines has been developed, ranging from the measuring microscope to KOCH's registering micro-photometer, which involves an ingenious application of the photo-electric cell.

Within the brief limits of this address I cannot hope even to enumerate more than a small fraction of the many appliances which the astronomer now has at his disposal. But I must mention here that large category of laboratory apparatus, including the electro-magnet, the vacuum tube in its many forms, the electric furnace and the long array of similar devices which the discoveries of ZEEMAN, STARK and other physicists have rendered of fundamental importance. I may also remind you of the astronomical significance of discoveries in radio-activity, theories of the structure of the atom, the laws of spectral series, and a host of other advances, which have so greatly enlarged the scope of our inquiries.

The combined effect of these developments has been, not merely to multiply our means of research, but to modify our point of view, and to bring it much more nearly into coincidence with that of the physicist. Many physical and chem-

ical phenomena have been recognized in the Sun and stars before they were known in the laboratory. Thus helium, first produced in the laboratory in 1895, was discovered in solar prominences in 1868. Nebulium, the predominant constituent of nebulæ, has not yet been found on the Earth. The effects of the selective absorption of light, which lie at the basis of spectrum analysis, were first interpreted by observations of the solar spectrum. Changes in the relative intensities of spectral lines due to reduction of temperature were first observed in sun-spots. Again, certain experiments beyond the range of the laboratory can be performed with the aid of celestial bodies. Thus, in order to help answer the question whether all large rotating bodies are magnets, we may examine the light of that immense rotating sphere, the Sun. And so I might go on to illustrate the advantage to the chemist or the physicist of studying astronomical objects, which frequently present facilities for tests or experiments difficult or impossible under terrestrial conditions.

But the converse view is the one I wish to emphasize: namely, the importance to the astronomer of interpreting celestial phenomena by means of laboratory experiments, where the exact conditions are known and are under perfect control. No method of research is more satisfactory than this, for none goes so directly to the heart of the question or eliminates more completely the danger of error.

In undertaking to deal with what I may call the laboratory method in astronomy, let me invite your attention to three phases of the subject. These involve:—

(1) The adaptation and use in the observatory of various laboratory instruments.

(2) The modification of the design of astronomical instruments so as to permit solar and stellar images to be studied under laboratory conditions.

(3) The imitation and interpretation of celestial phenomena by laboratory experiments.

In each case my treatment must be very fragmentary, based upon certain typical examples which serve to illustrate the point in view, but making no attempt to cover the ground exhaustively. In choosing my illustrations I have frequently

been guided by a desire to indicate opportunities for work with small and inexpensive equipments, such as any amateur may possess. In these days of great telescopes there is danger that an erroneous impression regarding the possibilities of limited resources may prevail. As a matter of fact, these possibilities are enormously greater than ever before, and no one who realizes the true state of affairs need fear that his means, however simple, are inadequate to advance knowledge. A great telescope, tho desirable or even essential for many purposes, is by no means required for much work of the highest class. Indeed, some of the discoveries I shall mention as the product of smaller instruments are quite beyond the reach of the largest telescope unless it be equipped with special auxiliaries.

(1) *New Instruments from the Physical Laboratory.*

Few recent illustrations of the advantages which may follow the intelligent application of physical methods in astronomy are more striking than that afforded by the selenium cell. The sensitiveness of selenium to light, which reduces its electrical resistance, has been known for many years. But it remained for STEBBINS, working with a standard 12-inch telescope at the University of Illinois, to demonstrate that important astronomical discoveries may result from the use of this principle. Better than selenium, and now adopted in its stead, is the photo-electric cell perfected by ELSTER and GEITEL. This consists of a clear metallic surface of sodium, potassium, rubidium or cæsium, sealed within a glass bulb containing helium at low pressure. When exposed to light the metallic surface gives off negatively charged particles and thus acquires a positive charge easily measured with a delicate electrometer.

Here is a photograph[1] of Dr. STEBBINS' telescope with the cell in place. Applied to a star *(δ Orionis)* suspected of variability, but showing no changes appreciable to the eye, the cell has yielded measures represented by this intensity curve. In this way a large new class of variable stars, formerly regarded as invariable, is rendered available for study. Conspicuous among

[1] Here and thruout his address Dr. HALE illustrated his points with lantern slides. The experiments described in the last section of the address were beautifully carried out in the lecture room.—EDITORS.

these are many spectroscopic binaries, whose orbital motions have been revealed by the spectrograph. It is unnecessary to say that a means of measuring their corresponding fluctuations in light, previously beyond reach in the vast majority of cases, will be of great service to the astronomer. Obviously the photo-electric cell can be applied to many other astronomical and physical purposes, and we may confidently look to it for many discoveries in the future.

Another powerful weapon of attack was disclosed when LANGLEY invented and applied the bolometer in 1880. If a thin wire, say of steel or platinum, is heated, its electrical resistance is altered. Suppose this wire is made to serve as one arm of the delicate device known as Wheatstone's bridge, used in every electrical laboratory for resistance measurements. When properly balanced, and employed with an exceedingly sensitive galvanometer, the bolometer is capable of detecting a change in temperature of less than a millionth of a degree. Its extreme sensitiveness to radiation led LANGLEY to explore the invisible infra-red spectrum with its aid. Thus he disclosed an extensive region, unknown to the eye or the photographic plate, and fully ten times as long as the entire visible spectrum from red to violet. Glass is as impervious as steel to the longer waves of the infra-red, and rock-salt lenses and prisms must be used to transmit them. In its perfected form, as employed by ABBOT, the bolometer has become an automatic recording instrument of perfect reliability, serviceable in a score of ways to the student of astrophysics. Already, in conjunction with an improved pyrheliometer, it has demonstrated the Sun to be a variable star, and measured its fluctuations in heat radiation.

The detection and measurement of the almost infinitesimal heat which reaches us from the stars is a task of very recent achievement, carried to a high degree of success by COBLENTZ at Mount Hamilton in 1914. NICHOLS, using a radiometer sensitive to the light of a candle five miles away, (assuming no atmospheric absorption) had measured the heat radiation of *Arcturus* and *Vega* at the Yerkes Observatory in 1900. PFUND improved materially on his results, and COBLENTZ has now

accomplished the remarkable task of measuring the heat from stars beyond the limit of naked-eye visibility.

The apparatus employed for this work is an improved form of thermopile, an instrument which dates from 1830, when NOBILI and MELLONI constructed from strips of antimony and bismuth a heat-measuring device ten times as sensitive as the best thermometer of the day. The thermopile of COBLENTZ, consisting of a very small bismuth-platinum junction supported in a vacuum chamber at the focus of the three-foot mirror of the Crossley reflector, would give a galvanometer deflection of 1 mm. when exposed to the radiation of a candle 53 miles away, if there were no atmospheric absorption. Dr. COBLENTZ believes that the sensitiveness of the thermopile-galvanometer combination can be increased sufficiently to detect the radiation from a candle 500 miles away, if employed in conjunction with a seven-foot mirror. Under such conditions work of great value could be done on the spectral energy curves of stars.

So far our attention has been concentrated upon certain electrical devices which act like super-senses, applicable where other means at our disposal are sluggish or wholly inert. Let us now turn to another group of instruments, which may be used in lieu of the most powerful spectroscopes for the refined analysis of light.

MICHELSON'S interferometer has been applied with success in a score of different fields. It serves to render visible the twisting of a massive steel bar by the fingers, to test the relative motion of the Earth and the ether, or to measure the length of the international meter in terms of that invariable unit of reference—the light-wave. From the point of view of the spectroscopist one of its greatest services is the converse measurement of the absolute wave-length of light.

In this field the interferometer of FABRY and PEROT is also of the highest importance. In the extremely simple and convenient form of the *étalon,* best consisting of two plates of lightly silvered fused quartz held perfectly parallel at an invariable distance of a few millimeters by short bars of invar, it now plays a leading part in high precision spectroscopy. The circular fringes produced when the light of mercury vapor

is allowed to fall on an étalon are of great beauty, representing not only the chief lines but also their faint satellites in the form of companion fringes. The slightest change in the wave-length of the light is shown by expansion or contraction of the fringes. So sensitive is this interferometer that the Doppler effect can be demonstrated experimentally by its aid. It is only necessary to provide a wheel with projecting paddles of white paper, and illuminate it with green mercury light when it is spinning at high velocity. The motion of the paddles toward or away from the observer will be indicated by a slight change in the diameter of the fringes, due to a corresponding change in the effective wave-length of the light reflected back from the moving paddles. Thus the very method which we utilize with the spectroscope for the study of the Sun's rotation or the radial motions of stars can be experimentally illustrated in the laboratory.

Time fails me to describe FABRY's beautiful investigation with the interferometer of the moving gases in the *Orion* nebula, or to speak of those ingenious instruments, the echelon grating of MICHELSON and the LUMMER-GEHRCKE parallel plate. But I cannot fail to mention the remarkable advances recently made in the ruling of diffraction gratings, the chief reliance of the spectroscopist in almost every class of laboratory and observatory work demanding high dispersion. A century ago FRAUNHOFER of Munich, after making the first gratings from wires stretched between two screws of very fine pitch, succeeded in ruling parallel lines on glass at the rate of 400 to the millimeter and even finer. With these he successfully observed the dark lines of the solar spectrum. RUTHERFORD's ruling machine, constructed by CHAPMAN in 1879, yielded gratings of excellent quality which were applied by RUTHERFORD, DRAPER, YOUNG and others to the study of the solar spectrum. A still greater advance was made in 1882 and later, when ROWLAND's large concave gratings suddenly advanced spectroscopy from the qualitative to the quantitative stage by rendering possible measurements of the highest precision. With ROWLAND's reconstructed machine ANDERSON has recently ruled gratings of extraordinary perfection, having a resolving power fully twice that predicted from theory.

Finally, to crown this long list of achievements, MICHELSON has recently ruled a ten-inch grating having about 622 lines to the millimeter, which gives superb resolution even in the eighth order.

We must now leave this phase of the subject, tho it is far from exhausted, and consider how we may acquire some of the chief advantages of laboratory conditions in astronomical spectroscopy.

(2) *Laboratory Conditions in Work with the Telescope.*

I had hoped, when first outlining this address, to include in it a brief sketch of the development of the astronomical telescope. It would have been interesting to describe the rise and progress of the refractor, so long delayed by the absence of suitable optical glass, and to trace the origin of the reflector, its curious decline during the second half of the last century, and its remarkable development in recent years. It might have been profitable also to emphasize those sterling qualities of the refractor which so firmly maintain its place in the observatory, in spite of the advance of its powerful rival. Its convenience of manipulation, surprising insensibility to temperature change, and large field of view are not shared by the reflector, tho for perfect achromatism and light-gathering power per unit cost the latter stands alone. Both instruments therefore have important places to fill, and it is merely a question of apportioning to each its most suitable field of observation. FOR BURNHAM'S, AITKEN'S, and HUSSEY'S observations of double stars, BARNARD'S measures of faint satellites and other difficult objects, FOX'S and SLOCUM'S photographs of solar prominences, RITCHEY'S photographs of the Moon, the photographic determinations of parallaxes so ably initiated by SCHLESINGER, and many other classes of work the Lick and Yerkes refractors, which we may take as examples, have proved of immense value. And while large reflectors might now be preferred to them for the photographic investigation of the spectra of the fainter stars, the splendid spectroscopic work of CAMPBELL, FROST and others with these telescopes show how efficient they are in this department.

The discussion of telescopes into which I am so seriously tempted to fall would give due credit to the wide field of the portrait lens, utilized so effectively by PICKERING in cataloging the spectra of several hundred thousand stars and by BARNARD in his photographic studies of the Milky Way. The advantage of the photographic correction for the two-lens refractor, so clearly exemplified in SCHLESINGER'S recent parallax work with the BRASHEAR 30-inch at Allegheny, would also demand consideration; but in spite of its effective recognition in this instance, it is fortunate that large visual refractors are still available for those investigations in which the eye and micrometer are indispensable. In fact, the entire discussion would illustrate how the recognition and utilization of various optical and mechanical possibilities have given us a whole series of telescopes, each adapted for work in certain fields.

Of the types of telescopes thus developed there is one which falls within the subject I have undertaken to sketch. This is the instrument which brings a solar or a stellar image into a laboratory for study by spectrographs or other apparatus too large or too delicate to serve as attachments to moving telescope tubes.

The solar spectroscope, as first used by KIRCHHOFF and BUNSEN, was a fixed laboratory instrument fed with sunlight by a heliostat. Later it became an attachment of the equatorial refractor, which permitted its application to the study of sun-spots, prominences and other details of the solar image. In this form it grew toward a maximum focal length of about 3½ feet, limited by the carrying capacity of the telescope and other considerations. ROWLAND'S researches with concave gratings of 21 feet focal length revolutionized laboratory spectroscopy, but it was obvious that spectroscopes of equal power could not be attached to a moving telescope. Fixed telescopes giving a large and sharply defined solar image thus became necessary.

These involve the use of a heliostat or coelostat, sending a beam of sunlight in a fixed direction, usually horizontal or vertical. In the latter case, the coelostat, second mirror and object-glass (here of 150 feet focal length), may be mounted at the summit of a steel tower, while the spectrograph, of 75

feet focal length, stands in a well excavated in the earth beneath it. The great stability of the spectrograph and the constancy of temperature of the grating at the bottom of the well, are among the chief advantages of this form of instrument. The solar image, over 16 inches in diameter, is thus available for study under the best of laboratory conditions.

The advantages of solar spectrographs of great focal length are easily illustrated. Four photographs of the solar spectrum, taken with spectrographs of 42½ inches, 18 feet, 30 feet and 75 feet focal length respectively, show striking differences in the separation of lines. This is partly due in the last step (30 feet to 75 feet), to the use of a MICHELSON grating in place of the smaller ROWLAND grating employed with the first three spectrographs. But a comparison of the first three spectra will show that the improvement is mainly due to the gain in linear dispersion and photographic resolution effected by increasing the focal length of the spectrograph. Details hopelessly confused in the small scale spectra by the blending of lines are plainly apparent under the higher linear dispersion, and the precision of differential measurements of the finer lines is fully proportional to the increase in scale.

These large spectrographs are of the auto-collimating type, i. e. the rays are returned by the grating thru the collimating lens, which thus serves also to form the image of the spectrum near the slit. A spectrograph which has some optical advantages is that in which the collimator and camera are inclined at an angle of from 25° to 60°, in order to utilize the increased dispersion thus obtainable.

The gain effected by high dispersion in solar spectroscopy, which has recently been utilized in many classes of work, naturally suggests a similar step in stellar spectroscopy. Here, however, the conditions are essentially different, partly on account of the faintness of the stars, and also because complete success has already been achieved, at least in the measurement of stellar motions, with spectrographs of moderate dimensions attached to equatorial telescopes. It is astonishing to think how much has been accomplished in this field by CAMPBELL and his colleagues since the Mills spectrograph entered upon its pioneer labors with the Lick telescope in 1896. From the

very outset beautifully sharp photographs of stellar spectra and velocity measures of the highest precision have been obtained with this instrument, which in its perfected form still continues its work on Mount Hamilton, supplemented by a similar instrument in the southern hemisphere. No method of improving on the results obtained with these spectrographs is yet in sight, and the high dispersion spectrograph which I am about to mention is intended for work of another kind.

In the study of the physical nature of stars we must deal with problems like those of solar physics, in which extremely minute displacements of spectral lines may be interpreted as the effect of the pressures and motions of vapors lying at different levels in stellar atmospheres. Valuable results in this field have already been obtained by ADAMS with the 60-inch Mount Wilson reflector, and the 100-inch telescope mounting now under construction has been designed so as to permit the use of a stellar spectrograph of from 30 to 50 feet focal length. This is to be mounted on a massive pier in a constant temperature chamber, so that the exposures may be continued for several successive nights, or until an impression of the highly dispersed and therefore feeble spectrum has been obtained.

(3) *The Imitation of Celestial Phenomena by Laboratory Experiments.*

We have now glanced at two phases of the laboratory method in astronomy, involving, on the one hand, the adaptation of various physical instruments for use with the telescope, and, on the other, the modification of telescope design in order to bring solar and stellar images into constant temperature laboratories. Let us next turn our attention to a no less important possibility: the interpretation of celestial phenomena by laboratory experiments. Many examples of such work might be given, but I have ventured to choose one from recent experience, which is easily illustrated, and may have some suggestive value, especially to those who lack extensive instrumental equipment. I refer to a series of simple vortex experiments bearing on the nature of sun-spots and flocculi.

In order to make these experiments intelligible I must first recall the circumstances under which they were developed and

the hypothesis they are intended to test. If we photograph the Sun with a spectroheliograph which excludes from the photographic plate all light except that of the red line ($H\alpha$) of hydrogen, we find what appear to be vortex phenomena associated with sun-spots. In fact, we seem to be looking into immense whirlpools, which sometimes sweep clouds of hydrogen into the spots at high velocities. This leads us to infer, as Sir JOHN HERSCHEL and FAYE did long ago, that sun-spots may be closely analogous to tornadoes in the Earth's atmosphere. Modern electrical experiments tell us that there must be many electrically charged particles in the Sun, and these would produce a magnetic field if whirled in a vortex. From this point of view a sun-spot resembles a helix of wire, thru which an electric current is flowing. But how are we to find whether a magnetic field is actually present in the spot?

Fortunately ZEEMAN has shown us how to recognize the very characteristic effects of magnetism on light. We pass a spark between two rods of iron supported between the poles of a magnet. The lines of the iron spectrum, ordinarily single, are split into three or more components the moment the current is sent thru the magnet coils. Hence the iron lines should behave similarly in a sun-spot. We photograph the spot spectrum, and find the lines to be split into triplets, quadruplets, quintuplets, etc., the number of components being the same, line for line, as in the laboratory. These are polarized in a most characteristic way, so that either side line of a triplet can be cut off at will by a Nicol prism and quarter-wave plate.

Here is an iron triplet in the sun-spot, which also turns out to be triple in the laboratory. We apply the polarization test, and cut off its components at will. Next to it is another iron line, which appears as a quadruplet both in laboratory and spot and answers equally well to the polarization test. So we may go on, comparing in spot and laboratory all the lines of iron and other elements, measuring the strength of the magnetic field in different parts of the spot and at various levels above it, and determining the inclination of the lines of force to the line of sight.

These magnetic experiments, which are supported by EVER-

SHED's and ST. JOHN's spectroscopic observations of the whirling vapors in spots, justify the assumption that sun-spots are vortices. Let us try to indicate by some simple experiments how such vortices may arise and what forms they may assume.

Everyone has seen a whirling dust-storm and knows by hearsay, if not by experience, of the destructive tornado or the waterspout. It is easy to imitate these phenomena by an experiment due to WEYHER. Here is a shallow cylindrical box, with radial vanes, mounted on a vertical axis. When spun at high velocity, it draws up the air from below, and produces a very passable imitation of a waterspout rising from a pan of steaming water. More plainly visible to an audience, and more closely analogous to whirling prominences sometimes observed on the Sun, is this "firespout" produced by spinning our disk above a flame rising from cotton saturated with gasoline.

In the Earth's atmosphere any column of air, carried rapidly upward by convection, begins to whirl and becomes a columnar vortex. In the Sun, on account of its high temperature, the ascending convection currents are much more numerous and violent, and similar vortex phenomena must be of frequent occurrence. Here, for example, is an illustration of vortex motion in a solar prominence, as seen at the edge of the Sun. The analogy with a terrestrial dust whirl is apparently very close, and we may advantageously push our inquiry further.

Sun-spots, which lie at the base of the solar atmosphere, probably originate within the photosphere. It has been shown by FOX and others that they are invariably preceded by eruptions, which represent hot masses of gas rising rapidly from the interior to the surface. Thus a columnar vortex would be set up, which might resemble a waterspout if we could see it below the photosphere.

So far we have been thinking of single spots. But sun-spots have a remarkable tendency to appear in pairs, the members of which are of opposite magnetic polarity, i. e. their electric vortices are whirling in opposite directions. Can we throw any light on this peculiarity by laboratory experiments?

Here is a flexible spiral spring of closely coiled brass wire, with some disks of wood threaded on it. We hang it vertically in a tank of water and spin it rapidly with an electric motor.

The water close to the wooden disks is set whirling by the friction, and we have a columnar vortex resembling a single sun-spot. At low speeds this vortex remains nearly vertical, but as the speed increases it begins to bend, its lower end rising toward the surface until finally it assumes a semi-circular form, and moves forward thru the water at right angles to its plane, thus rotating about the shaft of the motor. It is interesting to watch the depressions and whirls in the water before the free end reaches the surface. These correspond in the hypothesis to the incipient spots which frequently form and disappear at the incomplete end of a bipolar sun-spot group.

But why does the semi-circular vortex rotate, and is there any analogous motion of sun-spots? Here is a box containing smoke. If I strike it sharply a smoke-ring is formed and moves rapidly thru the air. This familiar experiment may be repeated in a much more effective manner described by MACH. If a little colored liquid is forced from a tube in water a vortex ring will be formed and move thru the tank. The structure of this ring is beautifully shown by these photographs, which are very easily made. Let me call your attention to two points of importance. Note, in the first place, that as the outer circumference of the vortex ring is naturally greater than its inner circumference, it will be more retarded by friction with the surrounding water. Hence the ring will move forward in a direction which corresponds with the direction of rotation of the fluid at its inner edge. It was mainly for this reason that our flexible columnar vortex, when turned up into the form of a semi-circular vortex ring, moved forward thru the water. As one end was fixed, it was compelled to rotate about the motor shaft. The smoke ring, or liquid vortex ring, being entirely free, moves forward at right angles to its plane. The second point is one which may have a bearing on the structure of the hydrogen flocculi surrounding bipolar sun-spots. You will notice that the appearance of the vortex ring is not precisely the same in this side view of its upper and lower faces. Above we see a hood or arch, which is absent below, where the stream lines are straight and axial opposite the center of

the ring, and become more and more convex on either side of this axis. We will return to this presently.

Our hypothesis suggests, then, that a typical bipolar sun-spot is like half of one of these vortex rings. If so, it should exhibit the motion of a vortex ring, and move at right angles to the line joining the spots. As this line usually lies nearly east and west on the Sun, a bipolar spot should move to the north or south, its direction of motion being determined by that of the inner edge of the ring.

Hence we must know the law of rotation of sun-spot vortices, which is indicated by the figure, if recent observations may be trusted. According to this, low latitude spots should move toward the equator, while high latitude spots should move toward the poles. Both CARRINGTON and DYSON found small average motions in these directions for low and high latitude spots, but it remains to be seen whether a rediscussion of the the material, eliminating single spots and averaging for the correct zones of latitude would correspond equally well. Then would come the question of the spot velocities, which now appear to be too low. But without dwelling on these points, which require additional solar and laboratory work, we may turn to the last illustrations I shall present.

In the solar atmosphere near sun-spots, as I have already remarked, there are extensive vortex phenomena, which can be photographed with the red line ($H\alpha$) of hydrogen. Some have regarded these as hydro-dynamic vortices, but others have considered them to represent the paths of electrically charged particles as defined by the magnetic fields in sun-spots. Another simple experiment may help us to see what hydro-dynamic influence a low-lying sun-spot vortex, single or double, would have on the solar atmosphere above it.

Let the water in this tank represent the solar photosphere. Just below the surface, and extending nearly up to it, is a small paddle wheel, with vertical axis, which may be set into rotation by an electric motor. The circulation in the liquid vortex thus produced is similar to that in a sun-spot; upward and spirally outward along the surface. Let us now stop the paddle and fill this enclosed space above the water with smoke. When the paddle is once more set into rotation a secondary

vortex is produced in the smoke, which is drawn outward on the water from the center of our artificial spot. The smoke at higher levels, flowing inward and downward to replace the smoke thrown outward below, moves along spiral stream-lines, plainly visible when sunlight is sent into the tank from one side. If we photograph these, as Mr. LUCKEY has done, and compare them with the stream-lines of the hydrogen flocculi surrounding sun-spots, we find some distinct points of resemblance, both for single and double spots.

Take, for example, the flocculi surrounding this bipolar spot group, as photographed by Fox with the Rumford spectroheliograph. Note the lack of symmetry on opposite sides of the axis, both in the flocculi and the smoke. Note also the resemblance to a moving liquid vortex, seen from a point in the plane of its ring. In all these cases the direction of rotation of spot, paddle, or ring is the same: clockwise on the right and counter-clockwise on the left. See how the stream-lines come in at one side nearly at right angles to the axis of the group, exhibit greater and greater curvature to the right and left, and form on the opposite side of the axis a hood or arch.

But we may go further. The spectroheliograph, by a method I will not stop to explain, permits us to photograph the solar atmosphere at many different levels. It is precisely as tho we were able to stand vertically above a tree (which we must assume to be transparent), and photograph sections at various heights thru the trunk and branches. Such pictures of the solar atmosphere about sun-spots show little or no evidence of vortex motion near the photosphere. But after a certain height is attained the stream-lines appear.

It is interesting to compare with these solar results the structure of the smoke vortices at different levels. This can be observed and photographed by illuminating a thin layer of the smoke at any distance above the water by sunlight passing thru a horizontal slit. At high levels the stream-lines are nearly radial, as they appear to be in the Sun. Lower down they are more sharply curved, and their resemblance to the solar flocculi is apparently very close in some cases. Still lower the curvature is more marked than we can detect in

the Sun, and we begin to have doubts as to the validity of the comparison. It is true that we finally reach a point, close to the water, where the inflow is suddenly changed to an outflow, and where the vortex structure is not in evidence. But the resulting appearance can hardly be said to be reflected in the structure of the low-lying calcium flocculi, and more study of this region is certainly needed. It must be remembered that the sudden change of density at the water level does not correspond with the gradual change of pressure in the solar atmosphere. The photosphere, instead of being a liquid, is a mass of metallic vapors, at a temperature above 6000° C, possibly containing small liquid particles in suspension. The pressure increases from vacuum tube values at high levels in the chromosphere to about one atmosphere near the photosphere. Thus it is evident that our experiments should be modified to conform more nearly to solar conditions before any conclusions can be based upon them.

A final experiment with our smoke vortices will show how we may imitate, at least superficially, the appearance of solar prominences near sun-spots. Here are some remarkable photographs by SLOCUM, showing a solar prominence in the act of being drawn into a spot. If we illuminate a vertical cross-section of our vortex with a beam of sunlight, we can see the smoke being drawn toward the artificial sun-spot in the water below it. Near the water level it turns sharply and moves outward again, an effect not seen in the Sun, unless it is partially indicated by the spectroscopic observations of EVERSHED and ST. JOHN.

In reviewing the evidence afforded by these experiments we clearly recognize that we have passed rapidly from the firm ground of demonstration, afforded by the existence of the ZEEMAN effect in sun-spots, to the doubtful region of conjecture, where we must be constantly on our guard against specious resemblances. The manner in which a flexible columnar vortex transforms itself into a semi-circular vortex ring is certainly suggestive, but this does not justify the conclusion that the same thing actually happens in bipolar sun-spots. As a matter of fact, when we examine complex spot groups showing, it is true, opposite magnetic fields at their

extremities, but containing innumerable small spots distributed along the axis of the group, we find it hard to believe that they represent a semi-circular vortex ring. Again, if we find in the hydrogen flocculi a nearly symmetrical structure resembling the lines of force between opposite magnetic poles, we may be led toward the view that electromagnetic, rather than hydrodynamic forces, are dominant. Such things teach us to realize that our experiments are imperfect, and should be brought more closely into harmony with solar conditions. But while exercising every precaution we need never fear to guide our successive steps by hypotheses, so long as we maintain an open mind, and adhere to that admirable definition of Sir JOSEPH THOMSON: "An hypothesis is a policy and not a creed."